

ARCHIVES
of
FOUNDRY ENGINEERING

ISSN (2299-2944)

Volume 18

Issue 3/2018

43 – 48

DOI: 10.24425/123599

7/3



Published quarterly as the organ of the Foundry Commission of the Polish Academy of Sciences

Abrasive-wear Resistance of Austenitic Cast Iron

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Received 14.05.2018; accepted in revised form 30.06.2018

Abstract

A research of wear resistance of an austenitic cast iron with higher resistance to abrasive-wear and maintained corrosion resistance characteristic for Ni-Resist cast iron is presented. For the examination, structure of raw castings was first formed by proper selection of chemical composition (to make machining possible). Next, a heat treatment was applied (annealing at 550 °C for 4 hours followed by air cooling) in order to increase abrasive-wear resistance. One of the factors deciding intensity of wear appeared to be the chilling degree of castings. However, with respect to unfavourable influence of chilling on machining properties, an important factor increasing abrasive-wear resistance is transformation of austenite to acicular ferrite as a result of annealing non-chilled castings. Heat treatment of non-chilled austenitic cast iron ($Equ_{Ni} > 16\%$) resulted in much higher abrasive-wear resistance in comparison to the alloy having pearlitic matrix at ambient temperature ($Equ_{Ni} 5.4\div 6.8\%$).

Keywords: Abrasive wear, Austenitic cast iron, Heat treatment, Nickel equivalent, Transformation of austenite

1. Introduction

Proper selection of chemical composition and heat treatment conditions of Ni-Mn-Cu cast iron should guarantee obtaining castings that are characterised by good machinability in raw condition and, after heat treatment, have good mechanical properties – similarly as in the case of austempered cast iron [1÷11] and high resistance to abrasive wear and corrosion [12,13]. This makes it possible to utilise this cast iron for cast parts of machines working in mining industry.

Selection of chemical composition is mostly based on the value of nickel equivalent Equ_{Ni} . This value, considering intensity of influence of individual elements on austenite stabilisation in cast iron [14÷19], can be calculated from the formula [20,21]:

$$Equ_{Ni} = 0.32 \cdot C + 0.13 \cdot Si + Ni + 2.48 \cdot Mn + 0.53 \cdot Cu \text{ [wt\%]}, \quad (1)$$

where:

C, Si, Ni, Mn, Cu – concentration of elements [wt%].

In the previously performed research works, a strict relation was found between the Equ_{Ni} value, matrix structure and hardness of cast iron Ni-Mn-Cu [20,21]. The limit Equ_{Ni} value of 16% was determined. If Equ_{Ni} is higher than this limit value, structure of raw castings is composed of austenite only. Further increase of Equ_{Ni} value results in higher thermodynamic stability of austenite. This restricts the possibility of changing the structure to one with higher hardness, by heat treatment. If Equ_{Ni} approximately equals to 16%, austenitic structure is obtained in raw condition, with rather low stability of matrix and relatively good machinability. This makes it possible to carry out machining of raw castings and,

next, to change the matrix structure to more hard by heat treatment. However, if Equ_{Ni} is lower than the limit value, partial transformation of austenite to martensite occurs during cooling-down in the mould, to a higher degree for lower Equ_{Ni} values. At the same time, hardness of raw castings increases, which, in turn, restricts the possibility to apply machining.

So, it is possible to select such chemical composition of cast iron that finished castings with high hardness (abrasive-wear resistance) were obtained in raw condition [21]. But, which is even more important, it is possible to obtain raw castings with relatively small hardness permitting them to be machined. Next, heat treatment can be carried-out to change the structure to more hard [7-9] and thus, most likely, more resistant to abrasive wear.

2. Purpose, scope and methodology of the research

In relation to the above, this research was aimed at determining influence of eutecticity degree and nickel equivalent on abrasive-wear of heat-treated cast iron Ni-Mn-Cu.

Examinations were carried-out on specimens coming from 16 melts of cast iron, designated 1 to 16, see Table 1. Chemical compositions and heat-treatment parameters were accepted on the grounds of previous research works [20]. Chemical compositions of the alloys changed within the following ranges: 2.0÷3.5% C; 1.5÷2.5% Si; 2.0÷4.5% Mn, 2.5÷4.5% Ni; 1.5÷2.5% Cu. This should, in most cases, ensure obtaining the alloys with desired features, i.e.:

- austenitic matrix of raw castings (possibly with small amount of martensite, which should not restrict machinability of castings);

- complete or almost complete absence of hard spots (slight chilling should not restrict machinability of castings);
- relatively good mechanical properties (sub-eutectic cast iron);
- possibility of partial transformation of austenite to acicular structure as a result of heat treatment consisting in soaking at 500 °C for 4 hours followed by air cooling.

Cast iron for the examinations was smelted in a laboratory medium-frequency furnace with SiC crucible type A35. Castings in form of shafts dia. 30 mm were made in shell moulds.

From the castings, test specimens were taken for chemical analyses, microscopic observations, hardness measurements and testing of abrasive-wear resistance.

Chemical analysis was carried-out spectrally with use of a glow discharge analyser GDS 750 QDP and a scanning electron microscope Quanta 250 equipped with a EDX detector. Inclination to chilling (creation of hard spots) was determined acc. to ASTM A367-55T, on 3C specimens solidified on a chill. Microscopic examinations were performed using a light microscope MA200 and a scanning electron microscope TM 3000. Brinell hardness was measured acc. to EN ISO 6506-1:2014-12 and Vickers microhardness was measured acc. to EN ISO 6507-1:2007.

Abrasive-wear resistance was determined by the „pin-on-disc” method on a tester made by Struers. Measurements consisted in abrading specimens dia. 25 mm pressed at 30 N against a diamond disk (grain size 45 to 53 μ m) cooled with water. Measurements were performed in six cycles. Each cycle lasting 5 minutes corresponded to sliding distance of 175 m. Therefore, each specimen was abraded for 30 min on the distance of 1050 m.

All tests were carried-out for each alloy on at least three specimens.

Table 1.
Chemical composition, eutectic saturation ratio S_C and nickel equivalent Equ_{Ni}

Alloy No.	Chemical composition [wt%]							S_C [/]	Equ_{Ni} [wt%]
	C	Si	Mn	Ni	Cu	P	S		
1	1.9	0.9	3.8	5.1	2.4	0.18	0.006	0.52	16.5
2	1.9	1.9	3.7	5.1	2.3	0.11	0.023	0.57	16.4
3	1.9	2.1	5.2	5.2	2.3	0.13	0.021	0.57	20.2
4	2.1	2.0	5.6	3.2	2.4	0.12	0.023	0.61	19.3
5	2.4	2.1	4.8	5.1	2.3	0.12	0.016	0.72	19.3
6	2.8	1.0	3.1	3.1	2.3	0.11	0.021	0.75	13.0
7	2.5	2.1	3.7	4.9	2.1	0.12	0.018	0.75	16.3
8	2.9	1.9	4.8	2.7	1.5	0.2	0.007	0.81	16.6
9	3.1	2.0	4.5	3.0	2.3	0.13	0.021	0.90	16.6
10	3.1	1.7	0.6	4.3	1.6	0.17	0.007	0.91	7.8
11	3.2	1.8	2.4	2.9	1.5	0.18	0.007	0.91	10.9
12	3.1	2.0	3.7	5.0	2.3	0.12	0.018	0.93	16.6
13	3.3	1.6	0.6	3.1	1.7	0.18	0.006	0.94	6.8
14	3.4	1.8	0.6	2.9	1.6	0.19	0.007	0.98	6.6
15	3.8	1.8	0.6	1.6	1.7	0.18	0.006	1.08	5.4
16	4.1	1.9	3.8	2.7	1.4	0.11	0.018	1.16	14.4

3. Results and discussion

3.1. Examination of raw castings

Features of graphite were evaluated acc. to EN ISO 945-1:2009 on unetched polished sections at magnification 100x. Results of observations are given in Table 2.

Table 2.

Eutectic saturation ratio S_C , chilling depth, percentages of high-carbon phases, hardness HBW of raw castings

Alloy No.	S_C [/]	Chilling depth [mm]	High-carbon phases* (% Fe_3C - % C_{graph} /features)	HBW [/]
1	0.52	45	100% Fe_3C - 0% C_{graph}	278
2	0.57	41	100% Fe_3C - 0% C_{graph}	276
3	0.57	42	100% Fe_3C - 0% C_{graph}	290
4	0.61	43	100% Fe_3C - 0% C_{graph}	299
5	0.72	36	80% Fe_3C - 20% /IE6	263
6	0.75	27	0% Fe_3C - 100% /IE6	268
7	0.75	26	0% Fe_3C - 100% /IE6	175
8	0.81	21	0% Fe_3C - 100% /IE6	148
9	0.90	20	0% Fe_3C - 100% /IE6	162
10	0.91	20	0% Fe_3C - 100% /IE5/6	395
11	0.91	18	0% Fe_3C - 100% /IE5/6	353
12	0.93	17	0% Fe_3C - 100% /IE4	145
13	0.94	17	0% Fe_3C - 100% /IE4	274
14	0.98	15	0% Fe_3C - 100% /IA4	271
15	1.08	12	0% Fe_3C - 100% /IA4	233
16	1.16	6	0% Fe_3C - 100% /IA3	251

* Fe_3C - cementite; C_{graph} - graphite

In the alloys with the lowest eutecticity degree ($S_C < 0.75$), complete chilling (alloys No. 1 to 4) or partial chilling with small percentage of graphite with interdendritic distribution IE6 acc. to EN ISO 945-1:2009 (alloy No. 5) was found. Structures of the alloys with higher S_C included IE graphite only. The alloys with S_C ranging between 0.75 and 0.90 included graphite size No. 6. In the alloy with S_C equal to 0.93, graphite size increased to No. 4. The alloys solidifying as eutectic (alloys No. 14 and 15) and hypereutectic (alloy No. 16) structures included graphite IA with size No. 4 and 3, respectively.

Matrix structures were observed on etched polished sections. Results are given in Table 3. The alloys are arranged acc. to decreasing Equ_{Ni} value.

Microscopic observations indicate diversity of matrix structures of the examined alloys. The most numerous group includes the alloys with exclusively austenitic matrix ($Equ_{Ni} > 16.0\%$). The next group is composed of the alloys in that austenite was partially transformed to the phase with morphology characteristic for martensite ($Equ_{Ni} < 16.0\%$). Because of lower hardness of this phase (550÷670 HV0.1N) in comparison to typical martensite, hereunder this phase is named "acicular ferrite". In the alloys with the lowest Equ_{Ni} values, presence of pearlite was found in their matrices.

Table 3.

Nickel equivalent Equ_{Ni} , composition of matrix, form of carbon in eutectic mixture and hardness HBW of raw castings

Alloy No.	Equ_{Ni} [wt%]	Matrix components* A - Fe_m - P [% - % - %]	Form of carbon in eutectic mixture	HBW [/]
3	20.2	100 - 0 - 0	Fe_3C	290
4	19.3	100 - 0 - 0	Fe_3C	299
5	19.3	100 - 0 - 0	C_{graph} + Fe_3C	263
8	16.6	100 - 0 - 0	C_{graph}	148
9	16.6	100 - 0 - 0	C_{graph}	162
12	16.6	100 - 0 - 0	C_{graph}	145
1	16.5	100 - 0 - 0	Fe_3C	278
2	16.4	100 - 0 - 0	Fe_3C	276
7	16.3	100 - 0 - 0	C_{graph}	175
16	14.4	83 - 17 - 0	C_{graph}	251
6	13.0	72 - 28 - 0	C_{graph}	268
11	10.9	27 - 63 - 0	C_{graph}	353
10	7.8	10 - 85 - 5	C_{graph}	395
13	6.8	0 - 0 - 100	C_{graph}	274
14	6.6	0 - 0 - 100	C_{graph}	271
15	5.4	0 - 0 - 100	C_{graph}	233

*A - austenite, Fe_m - acicular ferrite, P - pearlite

It results from the performed measurements that, according to the expectations, hardness of cast iron was decided by the ratio between quantities of graphite and cementite, as well as by matrix structure (mainly content of acicular ferrite).

3.2. Examination of heat-treated castings

Heat treatment of raw castings (annealing at 500 °C for 4 hours followed by air cooling) was determined based on many measurements [20]. Annealing resulted in structural changes of most castings, see Fig. 1 (pictures on the left show the raw cast iron, on the right annealed casts). Degree of such a change was strongly correlated with the nickel equivalent value. This phenomenon is illustrated by the diagram in Fig. 2.

In the alloy with the highest Equ_{Ni} value (No. 3), heat treatment did not cause any structural changes. Both before and after annealing, structure of the casting was composed of austenite only (Fig. 1a).

In the alloys that, like cast iron No. 3, showed austenitic structure after casting but contained smaller amounts of elements stabilising austenite (Equ_{Ni} 16.3÷19.3%), heat treatment caused partial transformation of austenite to acicular ferrite, see Figs. 1b and 1c. This was accompanied by increased hardness of the castings (Fig. 2). The lower Equ_{Ni} , the higher was austenite transformation degree and the related increase of hardness.

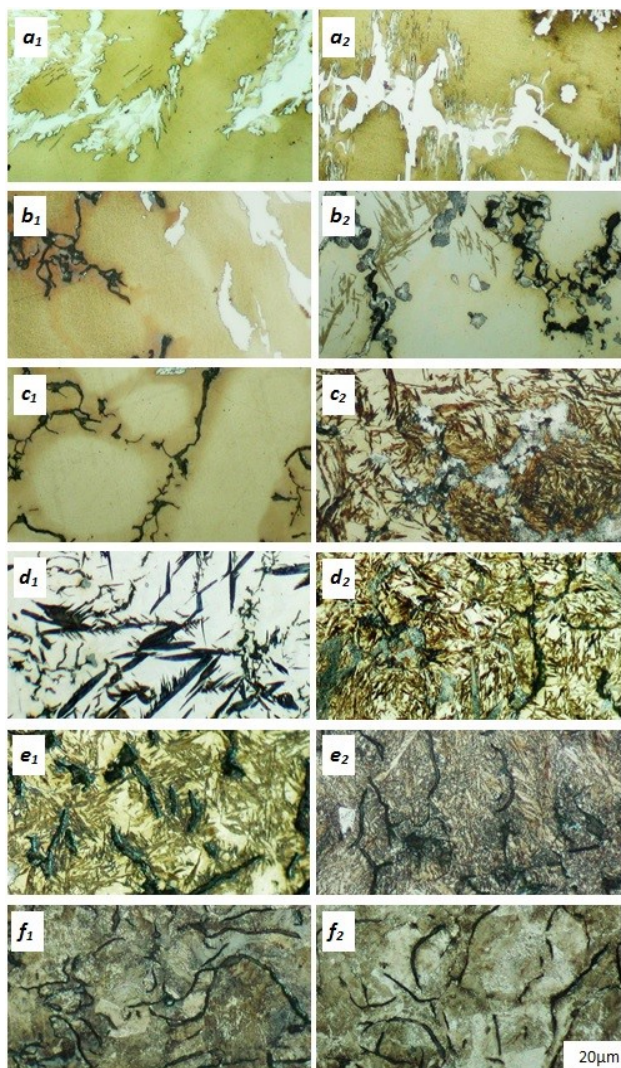


Fig. 1. Cast iron Ni-Mn-Cu: a) No. 3 ($Equ_{Ni} = 20.2\%$), a₁) raw – austenite, cementite, a₂) annealed – austenite, cementite; b) No. 5 ($Equ_{Ni} = 19.3\%$), b₁) raw – austenite, cementite, graphite, b₂) annealed – austenite, acicular ferrite, cementite, graphite; c) No. 12 ($Equ_{Ni} = 16.6\%$), c₁) raw – austenite, graphite, c₂) annealed – austenite, acicular ferrite, graphite; d) No. 16 ($Equ_{Ni} = 14.4\%$), d₁) raw – austenite, acicular ferrite, graphite, d₂) annealed – austenite, acicular ferrite, graphite; e) No. 10 ($Equ_{Ni} = 7.8\%$) e₁) raw – austenite, acicular ferrite, pearlite, graphite, e₂) annealed – austenite, acicular ferrite, graphite; f) No. 13 ($Equ_{Ni} = 6.8\%$), f₁) raw – pearlite, graphite; f₂) annealed – pearlite, graphite. Etched with $MnIFe$

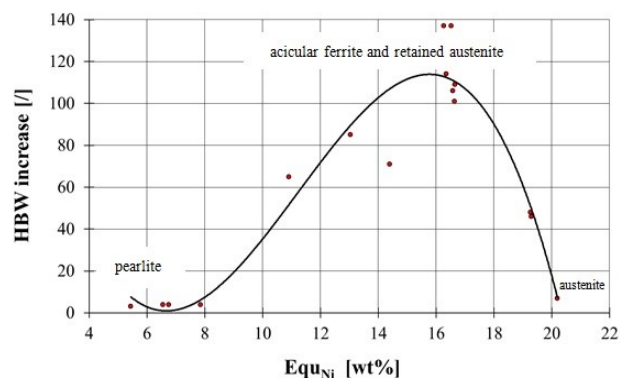


Fig. 2. Relation between nickel equivalent values Equ_{Ni} and increase of hardness HBW caused by heat treatment (annealing at 500 °C for 4 hours followed by air cooling) of castings

In the castings in which partial austenitic transformation occurred during cooling-down in the mould ($Equ_{Ni} 7.8\div 14.4\%$), annealing resulted in increased content of acicular ferrite in reverse proportion to Equ_{Ni} values, see Figs. 1d and 1e. The larger content of acicular ferrite in structures of raw castings (lower Equ_{Ni} value), the smaller was increase of this phase content caused by heat treatment. Namely, in the alloy No. 10 ($Equ_{Ni} = 7.8\%$) with the largest content of acicular ferrite in as-cast structure (Fig. 1e), annealing caused the smallest change of austenite transformation degree and thus the smallest increase of hardness in this group of alloys. Heat treatment of the alloys with larger and larger Equ_{Ni} value resulted in larger and larger effect of increased content of acicular ferrite and higher hardness of castings. The largest hardness increments of ca. 120 HBW units were found for the castings with $Equ_{Ni} \approx 16\%$ (low stability of austenite).

In the pearlitic cast iron ($Equ_{Ni} < 7.8\%$), heat treatment did not cause any important changes of structure or hardness of castings, see Fig. 1f. This resulted from too low concentration of elements stabilising austenite.

Examinations of abrasive-wear resistance were carried-out on annealed castings. Results are given in Table 4 and presented in form of diagrams of abrasive-wear rate in Figs. 3 and 4.

Analysis of the results indicates a complex effect of the factors deciding resistance of castings to abrasive wear. One of the most significant factors was chilling degree of the castings. The highest resistance to abrasive wear was found for the completely chilled alloys No. 1 and 2. In the partially chilled alloy, mass losses of the specimens were in average 30÷40% larger in relation to the completely chilled castings.

However, with respect to unfavourable effect of chilling on mechanical properties of cast iron, changing structures of raw castings by heat treatment should be considered the best way of increasing abrasive wear. The diagram in Fig. 3 shows the relation between nickel equivalent value and rate of abrasive wear of non-chilled castings.

Table 4.

Nickel equivalent Equ_{Ni} , contents of structural components in matrices, forms of carbon in eutectic mixtures, increase of hardness and rate of abrasive wear for heat-treated castings

<i>Alloy No.</i>	Equ_{Ni} [wt%]	Matrix components* A – Fe_m – P [% - % - %]	Form of carbon in eutectic mixture	Hardness HBW []	Increase of HBW []	Rate of abrasive wear [g/m ³ ·10 ⁴]
3	20.2	100 – 0 – 0	Fe ₃ C	297	7	2.20
4	19.3	92 – 8 – 0	Fe ₃ C	345	46	1.05
5	19.3	89 – 11 – 0	C _{graph} + Fe ₃ C	311	48	1.62
8	16.6	50 – 50 – 0	C _{graph}	254	106	1.20
9	16.6	45 – 55 – 0	C _{graph}	263	101	1.40
12	16.6	45 – 55 – 0	C _{graph}	254	109	1.15
1	16.5	35 – 65 – 0	Fe ₃ C	415	137	0.76
2	16.4	38 – 62 – 0	Fe ₃ C	390	114	0.86
7	16.4	34 – 66 – 0	C _{graph}	312	137	1.90
16	14.4	28 – 72 – 0	C _{graph}	304	71	1.81
6	13.0	25 – 75 – 0	C _{graph}	353	85	2.00
11	10.9	7 – 93 – 0	C _{graph}	418	65	1.24
10	7.8	2 – 98 – 0	C _{graph}	399	4	1.24
13	6.8	0 – 7 – 93	C _{graph}	278	4	2.57
14	6.6	0 – 0 – 100	C _{graph}	275	4	2.86
15	5.4	0 – 0 – 100	C _{graph}	236	3	3.62

*A – austenite, Fe_m – acicular ferrite, P – pearlite

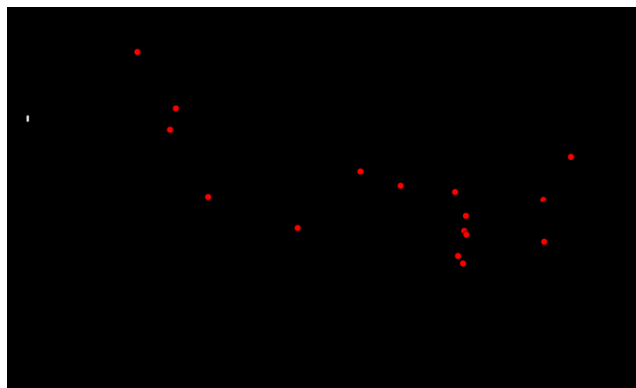


Fig. 3. Relation between nickel equivalent values Equ_{Ni} and rate of abrasive wear of non-chilled alloys

In the alloys with the lowest nickel equivalent values (5.4÷10.9%), increase of Equ_{Ni} resulted in clearly lower rates of abrasive wear of the specimens. This resulted from the fact that amount of acicular ferrite increased at the expense of amounts of pearlite or austenite. However, in the alloys showing austenitic structures of raw castings ($Equ_{Ni} > 16.0\%$), this relationship was no more so evident. This is indicated by differences between wear rates of the alloys with nickel equivalent close to 16.0%. It can be supposed that this results from differences between amounts and features of graphite in these alloys. It can not be also excluded that individual elements stabilising austenite differently influence abrasive-wear resistance. The obtained results indicate higher resistance of the alloys stabilised mostly with manganese.

However, obtaining unambiguous answers requires carrying-out additional research works.

The diagram shown in Fig. 4 makes it possible to compare wear rates of the alloys with low Equ_{Ni} values (5.4÷7.8%) and the alloys with Equ_{Ni} values higher than 16%. It results from the diagram that castings with similar hardness, made of austenitic cast iron ($Equ_{Ni} > 16.0\%$), show higher resistance to abrasive-wear than those with initial pearlitic structure ($Equ_{Ni} < 7.8\%$).

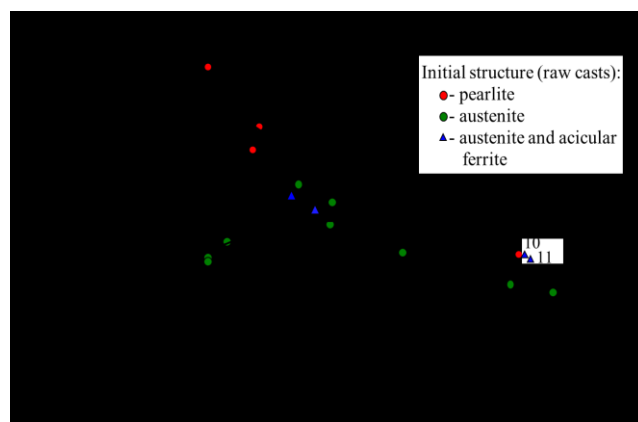


Fig. 4. Relation between HBW hardness of annealed castings with various initial structures and rate of abrasive wear

4. Summary

Analysis of the obtained results indicates diverse effects of the factors deciding abrasive wear of the examined cast iron.

One of the basic factors increasing wear resistance is chilling degree of castings. However, with respect to unfavourable effect of chilling on machinability, the important factor increasing abrasive-wear resistance appeared matrix structure, obtained after heat treatment (annealing of non-chilled castings).

In the alloys with the smallest values of nickel equivalent ($5.4 \div 10.9\%$), increasing this value resulted in clearly lower rate of abrasive wear of castings. This resulted from increased amount of acicular ferrite at the expense of pearlite or austenite due to heat treatment.

In the alloys with nickel equivalent values higher than 16%, showing austenitic structure in as-cast condition, this relationship was not so clear. It can be supposed that this resulted from percentage and characteristics of graphite, as well as of concentrations of individual austenite-stabilising elements in the matrix. However, formulating unambiguous conclusions requires carrying-out additional research works.

Heat treatment of non-chilled austenitic castings ($Equ_{Ni} > 16\%$) resulted in obtaining much higher abrasive-wear resistance in comparison to the alloys having pearlitic matrix in as-cast condition ($Equ_{Ni} 5.4 \div 6.8\%$).

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